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Fuel Poverty Potential Risk Index in the context of climate change in Chile

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ABSTRACT

Public housing policies face a challenge in order to meet not only the right to housing, but also an affordable and comfortable use for them. In this context, most of the studies related to fuel poverty are based on a diagnosis of existing conditions, but there is a lack of information focusing on how to predict the risk of fuel poverty in future dwellings considering a context of climate change. This research develops an index to assist policymakers in the decision-making process during the early stages of social housing allocation. The analysis is based on the applicability of adaptive comfort, the influence of climate change, the urban context and the building features. Energy use patterns and the ability to pay utility bills have been also considered for social housing in the Central-South of Chile. After that, several future scenarios are discussed considering the probable income and energy inflation rates. The potential risk variables that influence the early stages of design are also discussed. The results reveal that the Fuel Poverty Potential Risk Index is an effective tool to select appropriate housing for the most disadvantaged and vulnerable segments of society, considering the future climate, income and energy price trends.

1. Introduction

Energy poverty appears as one of the main challenges for the upcoming decades when talking about energy policy. The objective of the UN´s Millennium Development Goals (Rehfuess, 2006) is to eradicate extreme poverty, thus improving living conditions and facilitating the path towards sustainable development. Neither this document, nor the United Nations Framework Convention on Climate Change (UNFCCC) deal with the so-called access to energy (Reddy et al., 2000). However, energy consumption levels that satisfy basic necessities may not be reached in developing countries (González-Eguino, 2015) due to a complex interplay of power (Thompson and Bazilian, 2014), politics and commodification, together with asymmetry regarding the management, generation, distribution and final consumption of energy (Brown et al., 2014). As an example of this, the population with access to electricity in African countries is 72% (Legros et al., 2009), and in some of them, the only feasible energy source is burning wood or charcoal (Mandelli et al., 2014).

In developed countries, electricity is not the only energy source and access to energy services is mainly guaranteed. However, public policies oriented towards the lower strata of society have been increasingly developed in countries such as the UK (Robert et al., 2012a) and the US, (Department of Health and Human Services (U.S.), 2010). They aim at dealing with the transformations of the energy sector caused by climate change and the phenomena of energy poverty (González-Eguino, 2015).

Climate change has been profoundly analysed because of its influence, amongst a variety of economic sectors. In the construction industry, which represents approximately 40% of the energy consumption caused by human activities (Pérez-Lombard et al., 2008; UNEP, 2012); these figures are expected to grow over the coming years (IEA, 2013). For this reason, This has become a matter of attention for both governments and research institutions over the last few years. Starting with the foundation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, which has recently published its Fifth assessment report (AR5) (IPCC, 2014), there have been numerous studies that focus on climate change, the increase of gas emissions and the scarcity of natural resources. Along this line, sundry prediction models have been generated for various climate scenarios (Jentsch et al., 2008). Most of these models have been developed in the United Kingdom (Mylona, 2012), although they have increasingly extended throughout the international framework (Guan, 2009; Jentsch et al., 2013). Currently, the IPCC, supported by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), which is the most widely accepted organization in this matter, envisages multiple emission scenarios for the near future (IPCC, n.d.). According to several

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Nomenclature

AA	Apartment gross surface area
AL	Apartment location within the apartment block
AMEC	Average monthly energy consumption
AMECAC	Average monthly energy consumption using adaptive comfort
AEN	Asociación Española de Normalización
AR5	Fifth Assessment Report
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BT1	Tariff 1 for low voltage electricity
CASEN	Chilean national socioeconomic survey
CCS	Sustainable Building Code
CEN	Comité Europeo de Normalización
CO_2	Carbon dioxide
COP	Coefficient of performance
CLP	Chilean peso ($)
CTD	Technological Development Corporation
D	Distance from the shade element (m)
D_n	N decile
D_1	First decile
D_2	Second decile
D_3	Third decile
D_4	Fourth decile
DBT	Dry Bulb Temperature (C)
E	East
EC	Energy consumption (kWh)
EC_R	Real consumption (kWh)
EC_S	Simulation consumption (kWh)
EC_{SC}	Average monthly cooling consumption from the simulation (kWh)
EC_{SE+L}	Average monthly average consumption of equipment and lighting from the simulation (kWh)
EC_{SH}	Average monthly heating consumption from the simulation (kWh)
EER	Energy efficiency ratio
EN	European Norm
EPBD	Energy Performance of Buildings Directive
EPW	EnergyPlus Weather
EU	European Union
FP	Fuel poverty
FPAC	Fuel poverty adaptive comfort
FPI	Fuel poverty index
FR	Form ratio
FPPRI	Fuel poverty potential risk index
GCM	Global Climate Model
GHG	Greenhouse Gases
GHR	Global Horizontal Solar Radiation
H	Height of the shadow element (m)
H_t	Total hours of the study period (h)
H_d	Unoccupied hours of the study period (h)
H_c	Hours occupied in thermal comfort applying category III of the EN 15251:2007 norm pursuant the limits of Eqs. (3)–(5) (h)
HadCM3	Hadley Centre Coupled Model, version 3
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
INE	Instituto Nacional de Estadística de Chile
IRE	Inflation Rate Energy
IRI	Inflation Rate Income
LIHEAP	Low income home energy assistance program
LBL	Lawrence Berkeley Laboratory
MDS	Chilean Department of Social Welfare
MINVU	Ministry of Housing and Urban Development
N	North
NE	Northeast
NEA	National Energy Action
NO	Northwest
O	Orientation
OECD	Organization for Economic Co-operation and Development
OGUC	General Urbanism and Building Ordinance
P	Energy price ($/kWh)
P_C	Energy price for cooling ($/kWh)
P_{E+L}	Energy price for equipment and lighting ($/kWh)
P_H	Heating fuel or energy price ($/kWh)
PPI	Progress out of Poverty Index
O	West
RH	Relative Humidity
S	South
SCATs	Smart controls and thermal comfort
SE	Southeast
SEDI	Sustainable Energy Development Index
SL	Coastal South
SO	Southwest
TI	Threshold income
U	Thermal transmittance (W/m^2 K)
UK	United Kingdom
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WMO	World Meteorological Organization
Θ_{imax}	Upper limit of indoor operative temperature in Category III (°C)
Θ_{imin}	Lower limit of indoor operative temperature in Category III (°C)
Θ_{rm}	Running mean outdoor temperature for a specific day considering the daily mean external temperature of the 7 previous days (°C)
μ_{Dn}	Mean deviation
σ_{Dn}	Standard deviation
σ^2_{Dn}	Variance

research projects (Kalvelage et al., 2014; Rubio-Bellido et al., 2016; Wang and Chen, 2014), patterns for energy demand and consumption may be altered by climate change; therefore, they should be taken into account when devising schemes for energy supply and should also be carefully considered in order to prevent energy poverty.

Energy poverty, commonly linked with lack of access to energy sources and/or a deficient coverage of energy needs may be quantified in different ways, mainly considering high prices of fuel or energy, low building performance and low level of income.

The origin, evolution and discussion about the definition of energy poverty can be found in some key publications in this field (Robert et al., 2012b). For the sake of clarity in the discourse, the definition given by B. Boardman, which is considered a key text in the fuel poverty debate, is adopted in this manuscript (Boardman, 1991). Boardman states that “fuel poverty” can be defined as “the inability to afford adequate warmth because of the inefficiency of the home”; the threshold for affordability is established at 10%, twice the median household expenditure on fuel in 1991 (Liddell et al., 2012). Since then, despite the 10% threshold being broadly used as a general criteria to evaluate fuel poverty (Legendre and Ricci, 2015; O’Sullivan et al., 2015; Santamouris et al., 2013; Walker et al., 2014b), many authors have raised their concerns about the real significance of this figure. Methods

for measuring energy poverty can be classified into three groups: gathering the subjective impressions of residents about energy services in homes, analysing expenditure and the direct measure of certain energy services.

Several studies have come to light in recent years analysing fuel poverty and their implications in a variety of national contexts, such as Greece (Atsalis et al., 2016), Italy (Fabbri, 2015), Ireland (Healy, 2004; Healy and Clinch, 2002), India (Bhide and Monroy, 2011), Japan (Okushima, 2016) and the UK (Roberts et al., 2015; Rosenow et al., 2013). Others have placed focus on their implications for health (Lacroix and Chaton, 2015) risks for adults (Sharpe et al., 2015) and the death rate (Teller-Elsberg et al., 2016). From a perspective of geography (Walker et al., 2013), these have focused on rural areas (Pereira et al., 2010) (Roberts et al., 2015), the vulnerability of homes (Walker et al., 2014a) (Walker et al., 2014b), and even from a social justice point of view (Snell et al., 2015).

In recent years, several studies, which are more focused on the development of new indexes to measure fuel poverty, have come to light in order to clarify some issues pertaining to this term, as well as their implications for public policies:

- The Building Fuel Poverty Index (B_{FP}) (Fabbri, 2015), which establishes a relationship between building energy performance and the risk of fuel poverty in the Italian context, in order to quantify the number of existing buildings that need economic subsidies.
- The Progress out of Poverty Index (PPI) (Desiere et al., 2015) based on a Rwandan case-study, which consists of 10 weighted questions regarding the characteristics of households, whose primary sources can be observed and scored with respect to a poverty line.
- The Sustainable Energy Development Index (SEDI) (Iddrisu and Bhattacharyya, 2015), a composite index focused on establishing the sustainability level of both intra- and inter-generational needs and correlated to both the Human Development Index (HDI) and the Energy Development Index (EDI).
- The Energy poverty comprehensive evaluation index (Wang et al., 2015), focused on identifying the characteristics of China's energy poverty both at the national and regional levels, as well as the policy implications of energy poverty alleviation.

Those studies provide a solid scientific base which proves that fuel poverty is present nowadays and can have detrimental effects on occupants and be a burden on the finances of lower-income households. However, an evident shortcoming of predictive studies was noticed; that being, those focusing on predicting the risk of fuel poverty in dwellings that have not been built yet, considering future climate scenarios on the basis of climate change, rather than making a picture of the present situation. Besides, in mild climates such as the ones found in some zones of Chile (Rubio-Bellido et al., 2015a) and Europe (Rubio-Bellido et al., 2015b), the use of heating and air-conditioning devices can be decreased by using passive design and adaptive comfort in order to assure basic habitability conditions (Sánchez-Guevara Sánchez et al., 2016). Hence, it could be stated as a hypothesis that there is a potential application of these strategies in order to counteract the risk of fuel poverty. However, current standards are not usually fully aware of the potentiality of adaptive comfort, as they are mainly aimed at quantifying the energy consumption of buildings based on indicators related to CO_2 emissions, primary energy consumption or net supplied energy. These figures are summed up in a global indicator that informs about the energy efficiency of buildings (AEN/CTN 92, 2007). The standards generally quantify the buildings' energy efficiency taking into account energy consumption or CO_2 emissions associated to conditioning devices; this can be seen in the EN 15603:2008 and EN 15217:2007 standards (AEN/CTN 92, 2008, 2007). These values are obtained through energy simulations or other procedures that would predict the building's behavior, establishing its assigned temperatures and its operational hours. This temperature model is not very suitable when it comes to evaluating social housing, as it tends to misinterpret their real operation; these buildings tend to work in free oscillation, except under extremely cold or hot conditions (Chappells and Shove, 2005; Strengers and Maller, 2011). Additionally, in spite of the fact that the building sector in Chile accounts for 21.3% of the final energy consumption of the country, a large number of homes fall below the comfort temperature in winter because of the high price of fuel and the low income of their occupants (Bustamante et al., 2009). For those reasons, when quantifying energy consumption in such dwellings, it is necessary to keep in mind that the individuals tend to adapt their thermoregulation mechanisms in accordance to the exterior conditions by using windows, that is, natural ventilation. This can be evaluated through the adaptive comfort models (Fujii and Tanimoto, 2004; Humphreys et al., 2013) that, unlike other comfort standards, allow for a higher range of temperatures because they are dependent on the external temperatures in previous days.

The research projects RP-884 and SCATs (Smart controls and thermal comfort) have established the mainstream adaptive comfort models: ASHRAE 55-2013 (American Society of Heating, 2013; De Dear and Brager, 2002) and EN 15251:2007 (CEN, 2007; Nicol and Humphreys, 2002). These models find application in buildings with active systems that may or may not be used, depending on the severity of climate conditions; this is possible because easy access to operable windows is provided, along with adapting clothing to the thermal environment. Both models establish that the occupant's metabolic activity must be between 1.0 and 1.3 met and the clothing level between 0.5 and 1.0 clo.

Most of the current studies in the field of climatic adaptation of the residential sector are focused on studying comfort of their occupants, trying to reduce the use of active devices and fostering passive strategies (Van Hooff et al., 2015), an approach that represents how lower-income homes reduce their energy consumption in situations of thermal discomfort (Maller and Strengers, 2011).

When dealing with a context of households with lower or reduced incomes, Chile appears in the scene as a compelling case-study. It was the first South American country to join the OECD in 2010 (Organization for Economic Co-operation and Development, 2010) and, according to CASEN, poverty rates have been reduced from 29.1% in 2006 to 14.4% in 2013 (Ministerio de Desarrollo Social de Chile, 2015). This survey adopts an approach to measure poverty that connects with the theory of “capabilities framework” (Day et al., 2016) making a distinction between four factors contributing to poverty: Education, health, work and dwelling, and this last one accounts for around 30% of the total score of the index. This country´s policy towards vulnerable households has also been strongly influenced by a robust social housing program that started in 1936 and has been continuously enforced until present time. The national cadastre of social dwellings (Secretaría ejecutiva de desarrollo de barrios. MINVU, 2014) accounts for 344,402 subsidized units, classified according to several parameters related to year of construction, dwelling area, architectonic and constructive features, typologies, urban context and location, providing in this way with a good overview of the housing complex. These subsidized dwellings are mainly distributed in medium-rise blocks (3–6 stories) and 26,043 of which are located in the Bio-Bio region. They are organized into well-defined typologies. The most predominant in recent years, from 2005, are type A1 (medium-rise, compact with centralised access) and type B1 (medium-rise, compact, parallel blocks linked by external access); both types account for 40.5% of the total cadastre. The latest data from September 2016 indicates that MINVU is on its way towards delivering 764 additional social housing projects (Ministerio de vivienda y urbanismo de Chile (MINVU), 2016). According to the newest Chilean standard, this region´s climate is classified as SL (Coastal South) (DECON UC and Citec UBB, 2016), characterized by a mild climate that foresees a wide applicability of passive design strategies directly related to the adaptive comfort of the occupants, not only at the present time, but also in the event of a change in climate

conditions (Rubio-Bellido et al., 2015a). Therefore, it seems quite advisable to make use of these strategies in order to reduce the energy bill and, consequently, the risk of fuel poverty.

With regard to energy prices, and according to the 2012 report from the library of the Chilean National Congress, electricity prices for Chilean homes are placed in the middle tier of OECD members, with a price of 211 US$/MWh, being more expensive than countries such as the UK, France, Greece or Norway. If those prices are adjusted to the Purchasing Power Parity index (PPP), Chile takes 11th position with a price of 251 US$/MWh, sitting well above the OECD average (163 US $/MWh) and countries such as Austria, Slovenia, Ireland, Belgium, Holland and Japan. When compared within the Latin American context, Chile is the most expensive country regarding energy prices.

The evolution of those prices has shown a growing trend between 2006 and 2010, both in the OECD and in Chile itself; however, despite prices being similar in 2006 in both contexts, around 135 US$/MWh, in 2010 Chilean figures escalated up to 208.8 US$/MWh while the OECD average sat stagnant around 158.5 US$/MWh. Thus, it can be said that energy prices in Chile are expensive considering the OECD and the Latin American context, and also that they have experienced an abrupt rise in recent times. Talking about electric energy consumption itself, relevant data can be found in the latest 2010 report about energy use in Chilean homes (Corporación de Desarrollo Tecnológico de la Cámara Chilena de la Construcción, 2010). A Chilean household uses, as an average, 1805,7 kWh per annum; taking the average electricity price in Chile, which is 0.28 €/kWh (OECD, 2011) the average expenditure results in, roughly, 500 €. If compared with other OECD members, despite electricity prices for residents are high (only the Netherlands have more expensive electricity), Chileans spend little money on electricity (only Korean households are below Chileans in this respect). Therefore, these facts account for a scenario of energy vulnerability in Chile. The recent report by the ministry of energy (Soledad Palma Sierrra and Salvagno, 2016) states that, during wintertime, the interior temperature in dwellings located in the major urban areas (Santiago and Concepción) stays below 15 °C during 73% and 95% of wintertime. Likewise, in order to standardize the procedure of calculation of energy consumption on Chilean buildings, the first national standard in this matter has been recently published in August 2017 (INN Chile, 2017).

In this context, the question about the current state of affairs regarding fuel poverty in Chile arises. Though the government is not currently envisaging a policy framework directly related to this phenomenon, concepts such as energy affordability, the economic burden related to energy services and energy vulnerability are being posed in the political agenda. The program “Energy 2050” stablishes as objectives for 2035 achieving energy accessibility for 100% of vulnerable Chilean households and placing Chile amongst the 5 OECD countries with the lowest energy prices for residential and industrial use (Soledad Palma Sierrra and Salvagno, 2016). Besides, energy poverty is regarded as a challenge, being classified number 11 (define the concept and measuring of fuel poverty so that specific policies can be enacted for its solution) amongst the 38 strategic objectives that the Country has to reach in 2035 and 2050. In this sense, international cooperation is being provided by the United Nations, who is working together with the Ministry of energy in order to “*develop a theoretical and methodological framework to tackle fuel poverty in Chile*” (Ministerio de Energía, 2017).

Taking the aforementioned into consideration, this research is focused on the development of what has been called the Fuel Poverty Potential Risk Index. This index can be applied in the early stages of design of social housing, considering standards of adaptive comfort not only for the present, but also for future scenarios. This predictive index allows for a risk assessment of households when being allocated into a new dwelling, considering inflation rates, variations in energy prices and changes in patterns of energy consumption due to the influence of climate change.

2. Methodology

2.1. Theoretical basis

The fuel poverty indicator developed by Boardman is based on the following equation:

$$FPI = \frac{EC \cdot P}{I} \quad (1)$$

Where:

*EC*energy consumption (kWh)
*P*energy price used ($/kWh)
*I*household income ($)

Therefore, for its application, one needs to have the net household income, the home's energy consumption and the unit prices of the energy used. When FPI > 0.1, i.e., it exceeds 10% of the income, it is said that this home is experiencing a situation of fuel poverty.

Taking this formula as a base, the methodology hereby developed, proposes an adaptation to assess the risk of falling into fuel poverty for a household with a certain range of incomes (I), when being allocated in a subsidized dwelling. Data for household incomes (I) and energy prices (P) are extracted from available databases. Computer simulations are undertaken to calculate the forecasted EC values for different types of dwellings, depending on their architectonic and urban context.

Traditionally, fuel poverty is understood as a posteriori diagnosis situation where all factors of the Eq. (1) are known. However, in Chile, when it comes to assigning social housing, the potential risk of fuel poverty is not currently being taken into consideration. The current allocation mechanisms are done by merit, by lots, by similarity, by mediation or a combination thereof (Ministerio de vivienda y urbanismo (MINVU), 2008). Though, there are ways to calculate EC considering the actual comfort demands of inhabitants, thus preventing them from falling into FP (Sánchez de la Flor, 2015). The hereby proposed FPPRI effectively attempts to explore the interplay between EC, associated with the adaptive comfort model, and the phenomenon of FP. If the EN 15241:2007 (CEN, 2007) standard is considered, the number of hours during which users can achieve acceptable comfort conditions can be calculated (H_C) (Category III according to the EN 15251:2007); these conditions include the operation of windows and adaptation of clothing for moderate levels of thermal discomfort. After that, the occupation period of the dwelling can be effectively calculated as a fraction of the total number of hours considered in the study (H_t). In this way, a first approximation for the current EC (EC_R) can be obtained by applying a correction factor to the simulated EC (EC_S),

Table 1
Comfort temperature ranges in Category III in regard to prevailing mean outdoor air temperature (Θ_{rm}) EN 15251:2007.

Category - Limit		Prevailing mean outdoor air temperature Θ_{rm} - Comfort temperature			
		$\Theta_{rm} < 10$ °C	10 °C ≤ $\Theta_{rm} < 15$ °C	15 °C ≤ $\Theta_{rm} \leq 30$ °C	$\Theta_{rm} > 30$ °C
III	Upper comfort limit Θ_{lmax} (UIII)	25.0	$0.33*\Theta_{rm} + 18.8 + 4$	$0.33*\Theta_{rm} + 18.8 + 4$	27.0
	Lower comfort limit Θ_{lmin} (LIII)	18.0	18.0	$0.33*\Theta_{rm} + 18.8 - 4$	22.0

$$EC_R = EC_S \cdot (1 - \frac{H_d + H_c}{H_t}) \quad (2)$$

Where:

EC_s Simulated energy consumption (kWh)
H_t total hours of the study period (h)
H_d unoccupied hours of the study period (h)
H_c occupied hours in thermal comfort applying category III of EN 15251:2007 following the limits of equations 3–5 (h) and Table 1.

$$\Theta_{imax} = 0.33 * \Theta_{rm} + 18.8 + 4 \quad (3)$$

$$\Theta_{imin} = 0.33 * \Theta_{rm} + 18.8 - 4 \quad (4)$$

$$\Theta_{rm} = \frac{(\Theta_{ed-1} + 0.8*\Theta_{ed-2} + 0.6*\Theta_{ed-3} + 0.5*\Theta_{ed-4} + 0.3*\Theta_{ed-5} + 0.6*\Theta_{ed-6} + 0.2*\Theta_{ed-7})}{3.8} \quad (5)$$

Where:

Θ_{imax} upper limit of indoor operative temperature in Category III

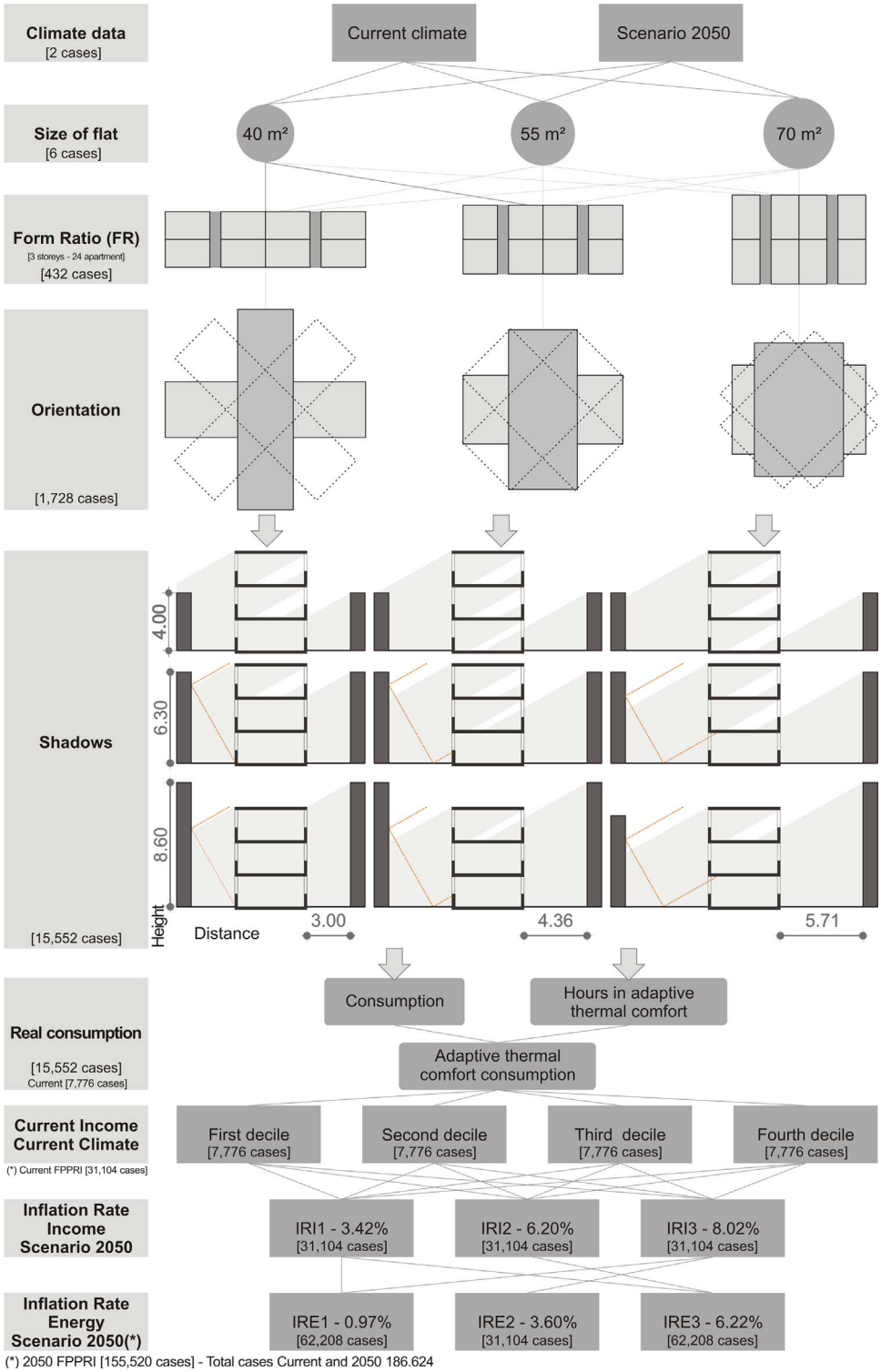

Fig. 1. Flowchart methodology.

(°C)
Θ_{imin} lower limit of indoor operative temperature in Category III (°C)
Θ_{rm} running mean outdoor temperature for a specific day considering the daily mean external temperature of the 7 previous days, Θ_{ed-1} being the daily mean external temperature for the previous day and Θ_{ed-2} the daily mean external temperature for the day before and so on (°C).

Thus, breaking down the consumption into heating, cooling, equipment and lighting and substituting in Eq. (1), the real energy consumption for both heating and cooling associated to the adaptive comfort potential pursuant Eq. (2), the following would be obtained:

$$FPI = \frac{EC_{SC}\cdot\left(1-\frac{H_d+H_c}{H_t}\right)\cdot P_C + EC_{SH}\cdot\left(1-\frac{H_d+H_c}{H_t}\right)\cdot P_H + EC_{SE+L}\cdot P_{E+L}}{I} \quad (6)$$

Where:

EC_{SC} average monthly cooling consumption from the simulation (kWh)
P_C kWh electricity price for cooling ($/kWh)
EC_{SH} average monthly heating consumption from the simulation (kWh)
P_H kWh energy of fuel price for heating ($/kWh)
EC_{SE+L} average monthly consumption of equipment and lighting from the simulation (kWh)
P_{E+L} kWh electricity price for equipment and lighting ($/kWh)

Eq. (6) would fit the standard definition for FP given in Eq. (1), even though it has been reformulated to include the influence of adaptive comfort. However, as said before, this would correspond to an a posteriori situation. This research is aimed at predicting the probability that the energy consumption of a dwelling represents a risk of fuel poverty for a household with given incomes. In consequence, we can establish a Threshold income (TI), which is defined as 10 times the EC of a dwelling, that is:

$$TI = 10\cdot\left[EC_{SC}\cdot\left(1-\frac{H_d+H_c}{H_t}\right)\cdot P_C + EC_{SH}\cdot\left(1-\frac{H_d+H_c}{H_t}\right)\cdot P_H + EC_{SE+L}\cdot P_{E+L}\right] \quad (7)$$

This would establish the limit for falling or not falling into FP according to Eq. (1). Additionally, taking the data from the CASEN survey, those results are fitted into a normal standard distribution using the equation:

$$f\left(x, \mu_{D_n}, \sigma^2_{D_n}\right) = \frac{1}{\sqrt{2\sigma^2_{D_n}\pi}} e^{-\frac{(x-\mu_{D_n})^2}{2\sigma^2_{D_n}}} \quad (8)$$

Here μ_{Dn} is the mean, σ_{Dn} the standard deviation and σ^2_{Dn} the variance for each one of the four deciles according to CASEN's data. Placing each one of the TI = x of EC into the four normal distributions, the FPPRI for a household inhabiting a dwelling whose energy consumption requires a TI to not fall into Fuel Poverty can be calculated as the area under the curve for each decile, that is:

$$FPPRI = \int_{-\infty}^{TI} f\left(TI, \mu_{D_n}, \sigma^2_{D_n}\right) d_{TI} \quad (9)$$

For a given decile D_n, the area of the curve ranging from the lower limit to the TI value represents the percentage of households that would fall into fuel poverty in the event that they inhabited said dwelling.

2.2. Building test models

To calculate EC_{SC}, EC_{SH} and EC_{SE+L}, different test models have been modelled using the following parameters: Size of the flat, location in the building, form ratio, orientation, distance from the building facing it and the height of that building (Fig. 1).

The simulations have been made with prototypes whose characteristics correspond to the A1 and B1 typologies for social housing projects developed by the Chilean Ministry of Housing and Urbanism (MINVU), found in Supreme Decree 47 (General Ordinance of the General Law on Urbanism and Buildings). There are 10 typologies for grouping social housing, and the types modelled are the two most common ones, representing 40.5% of the total number of 1495,000 social dwellings of MINVU in 2013. The values and variation limits for each variable are established as follows (Ministerío de vivienda y urbanísmo, 1992a; Secretaría ejecutiva de desarrollo de barrios. MINVU, 2014):

Surface area: The built surface areas of the flats are 40, 55 and 70 m^2 and their free height is 2.3 m.

Position in the building: In order to obtain results in terms of the position of the flat within the building, three height levels and eight flats per level have been considered. Thus, attending to their relative position in a given floor, there would be corner and central flats; these two types can be on the ground floor, an intermediate floor and the top floor.

Form ratio: The influence of the geometry of the flat's floor plan has been analysed starting from the FR factor, which is the relationship between the length and the width, contemplating three FR values, 0.6, 1.0 and 1.6.

Orientation: Taking a 360° arc in a clockwise direction as reference, the following orientations have been established: N (0°), NE (45°), E (90°), SE (135°). As the buildings have a double orientation, by simulating these 4 cases, the remaining 4 in the opposite flats is obtained: S (180°), SW (215°), W (270°), NW (315°).

Remote obstacles and shadows produced: These values have been analysed using the combination with the orientation variables, studying the four orientations with nine combinations of element possibilities that can generate shade over the building (Fig. 1). The distance (D) and height (H) values which will characterize the position and size of the shade element have been calculated starting from the winter solstice (worst case scenario). Thus, three values of H have been calculated so that the winter solstice projects cast shade over all the ground, intermediate or top floors for a distance (D) of three meters (minimum distance between buildings for the study area according to OGUC

Table 2
Limitation of transmittances, ventilation and infiltration for Concepcion, OGUC (section 4.1.10) and the Sustainable Building Code for Homes.

Case	U openings (W/m^2 K)			U envelope (W/m^2 K)			Ventilation l/(s*person)	Airtightness (ACH50)
	< 21%	21–60%	60–75%	Roof	Walls	Ground (m^2K)/W]*100		
OGUC	> 3.6	2.4–3.6	< 2.4	0.38	1.7	150	–	–
CCS							5.2	8
Lighting (W/m^2)	Dining-room		Kitchen		Bedroom		Hall	
	23		13		12		5	
Equipment (W)	Refrigerator		Television		Computer			
	250		50		200			

(Ministerío de vivienda y urbanísmo, 1992b)). The distance has been characterized so that for D = 4.36 m, 1/3 of the floor's height remains uncovered during the winter solstice and for D = 5.71, 2/3 are left uncovered (Fig. 1).

In all models, the building characteristics of Section 4.1.10 of SD 47 have been used, establishing the minimum transmittance for doors and windows (Table 2). The ventilation rate and airtightness requirements, as well as the thermal loads of lighting, equipment and occupation have been taken from the Chilean Sustainable Building Code (CCS in its Spanish acronym) (Ministerio de vivienda y urbanismo de Chile (MINVU), 2016). The thermal loads associated to the occupation are 100 W/person. For its application, the usage schedule of the homes and CCS' load percentages have been used (Fig. 2).

2.3. Evolution and database for the income levels and energy prices

Energy poverty is fundamentally associated with two indicators: income and energy price. Therefore, it becomes a necessity to establish economic scenarios on the basis of such variables in order to clarify the future trends in energy poverty. The evolution of incomes has been clarified through Chilean laws pertaining to the adjustment of the minimum wage during the 1987–2016 period, taking 1989 as a baseline year and adjusting the values to 2015 (*LEY-18647 03-SEP-1987 MINISTERIO DE HACIENDA - Ley Chile - Biblioteca del Congreso Nacional*, 1987). This has also been done through a New subsidiary survey on incomes in Chile 2010–2014, taking 2010 as a baseline year ("| Instituto Nacional de Estadísticas | INE, 2017," 2014). Regarding energy price, the consumer price index for the "*Electricity, gas and other fuels*" group has been extracted from the Chilean Bureau of Statistics for the 2000–2016 period, taking 2013 as a baseline year ("Índice de Precios al Consumidor - Base Anual 2013 = 100 | Instituto Nacional de Estadísticas | INE 2017, 2013). Taking this data as the base, inflation rates for the minimum wage (MSI), income (II) and electricity prices (CPIE) have been clarified (Fig. 3).

Minimum wage, income and electricity prices do not show a similar pattern (Fig. 3). Growth rates for minimum wages vary from 0.74% to 16.24% for the 1989–2016 period, with an average of 4.37%; growth rates for income fluctuate between 1.73% and 9.20%, with an average value of 8.02%; growth rates for electricity prices range between −15.26% and 28.71%, with an average of 6.22%. A close look at the data between 2010 and 2014, the period for which data about income could be gathered, reveals that the inflation rate for the minimum wage was 3.42%, some 4.60% below that for the average income, whereas the inflation rate for energy prices was 0.97%. Between 2000 and 2016 that rate was 5.26%. In order to consider the highest possible combination of financial contexts, 3 different growth rates have been considered regarding minimum wages, average income and energy prices, which will produce, at least, 9 different economic scenarios to be considered (Table 3). The inflation rates considered for the average income will be 3.42% (average MSI), 8.02% (average II) and the average between the former two during the period of study (6.20%). Inflation rates for energy prices will be set at 0.97% (Average CPIE 2010–2014), and 6.22% (Average CPIE) and finally the average between those two, that being, 3.60%. In this fashion, it is considered that the inflation rate for this parameter is similar to that for the minimum wage.

The initial selection of 9 combinations has been filtered and as a consequence has been reduced to five; the remaining four are not representative as they do not differ substantially from the five chosen. In this way, the scenarios that have been finally selected, represent how these three variables may behave in the future using an educated guess based on actual data.

The estimation of the risk of falling into energy poverty is related with the factors defined in Eq. (9). Because of this, for the FPPRI calculation, the first four deciles of Chilean household income obtained from the CASEN survey have been used; afterwards they have been projected to 2050 using three representative inflation rates (Tables 4 and 5). These represent the most vulnerable sectors of the population (Ministerio de Desarrollo Social de Chile, 2015). Said values represent the total household income divided by the its total number of members. Bearing in mind that according to CASEN, the average size of Chilean homes is 3.3 inhabitants, the values of Table 4 should be multiplied by 3.3 to obtain the incomes per each household (Ministerio de Desarrollo Social de Chile, 2015).

The energy prices (Table 5) have been obtained from the electricity rates of the concessionary company which has the highest distribution nationally in Chile according to Decree 1T for 2016 (Ministerio de Energía, 2012a). The calculation has been made based on the tariffing formulas from the aforementioned decree and from the values for the BT1 tariff with underground supply 1 for sector 1 of the Central Interconnected System 5 (CGE Distribución S.A., 2016; Ministerio de Energía, 2012b). Therefore, it is supposed that the tariffing system would not be altered from today to 2050.

2.4. Generation of weather data through GHG A2 Scenario Model

Future climate scenarios have been modelled by means of the UK Met Office Hadley Centre Coupled Model 3 HadCM3 ("Met Office Hadley Centre for Climate Science and Services," n.d.). This model takes into account the combination of the A2a, A2b and A2c scenarios in regards to CO_2 emissions. Using the morphing tool, CCWorldWeatherGen ("Met Office Hadley Centre for Climate Science and Services," n.d.), based on the studies of Belcher et al. (Belcher et al., 2005), the EPW file is morphed with the GHG A2 emissions scenario, obtaining sets of data for the 2050. The authors consider that the aforementioned predictions can be considered as a likely future development for this time-span. Although the HadCM3 A2 model is the most extensive to perform simulations for future predictions, and also, in spite of the numerous research papers that rely on its basis, some considerations should be made with regard to its accuracy and

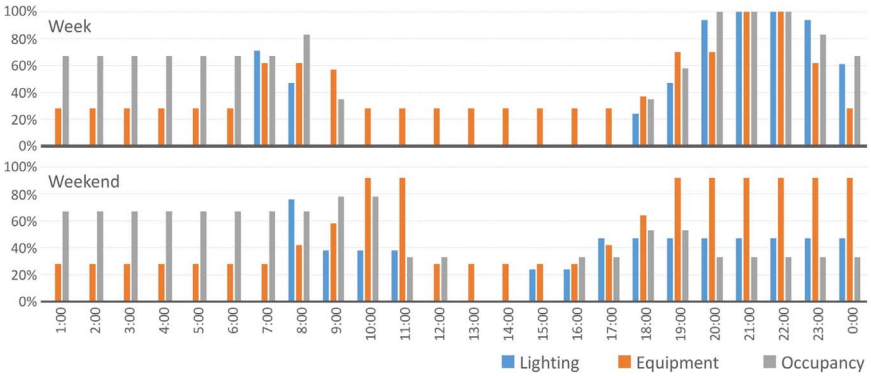

Fig. 2. Usage schedule of the homes and the load percentages.

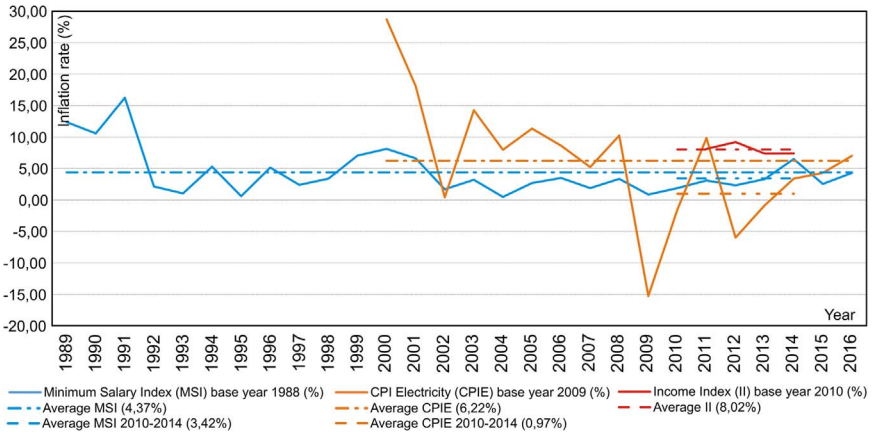
Inflation rate (%)
Year
Minimum Salary Index (MSI) base year 1988 (%)
CPI Electricity (CPIE) base year 2009 (%)
Income Index (II) base year 2010 (%)
Average MSI (4,37%)
Average CPIE (6,22%)
Average II (8,02%)
Average MSI 2010-2014 (3,42%)
Average CPIE 2010-2014 (0,97%)

Fig. 3. Evolution of the inflation rate for Minimum wage (MSI), Electricity price (CPIE) and Income (II).

Table 3
Combinations of selected income and energy inflation rates.

Combinations	Inflation Rate average income (IRI) (%)	Inflation Rate Energy price (IRE) (%)	Difference
IRI1-IRE1[a]	**3.42%**	**0.97%**	**2.45%**
IRI2-IRE2	6.20%	3.60%	2.60%
IRI3-IRE3	8.02%	6.22%	1.80%
IRI1-IRE2	3.42%	3.60%	−0.18%
IRI2-IRE3[a]	**6.20%**	**6.22%**	**−0.02%**
IRI3-IRE1[a]	**8.02%**	**0.97%**	**7.05%**
IRI1-IRE3[a]	**3.42%**	**6.22%**	**−2.80%**
IRI2-IRE1	6.20%	0.97%	5.23%
IRI3-IRE2[a]	**8.02%**	**3.60%**	**4.42%**

[a] Selected combinations to be analysed.

limitations. Firstly, although this model can be applied to this case study, the resolution of the HadCM3 is primarily used for making predictions at a global scale. Secondly, it is based on EPW files from meteorological stations, thus microclimate effects are not consider. Thirdly, HadCM3 model foresees future trends for the average values regarding climate variables, but it is not capable of contemplating extraordinary natural phenomena associated with climate change. That said, the future scenarios that are used in this research should be understood as the most probable expected average climatic conditions for a given time-span and for open field boundary conditions with a margin of error that corresponds to the grid size of the HadCM3 model.

3. Energy consumption considering adaptive comfort, climate change, evolution of income levels and energy prices

3.1. Current scenario

Fig. 4 shows the comparison between simulated average monthly energy consumption without considering adaptive comfort and average monthly energy consumption considering adaptive comfort. For each one of them, FPI and FPPRI have also been plotted on the upper X axis and right Y axis respectively. All simulated dwellings have been represented in a scatter plot, comparing their situation according to both FPI and FPPRI, as well as considering their monthly energy consumption in relation to the income limit (10% of incomes) in order to clarify whether they fall into Fuel Poverty. Dashed diagonal lines represent the potential EC reduction when changing the assessment criteria from FP to the newly proposed FPPRI.

Table 5
Representative values of the electric bill. Current value and projections for 2050 considering three different inflation rates.

Charge	Current values (CLP)	2050 values (CLP)		
		IRE (0.97%)	IRE (3.60%)	IRE (6.22%)
Fixed	813.07	1128.93	2706.20	6326.19
Base	124.28	172.57	413.66	967.01
Additional > 430 kWh	166.61	231.33	554.53	1296.31

The income limit for the first decile using FPI in all considered cases considered exceeds 0.1 (10% of the income), whereas the situation differs if FPPRI is applied. For 40 m^2 apartments, 78.05% of all cases fall into FP, thus their allocation criteria should be strongly focused on the affordability of the energy bill. Moreover, if FPI and FPPRI are compared for all the FR considered, FPPRI offers an EC reduction percentage of between 47.88% and 87.64%, with average values of 73.11% when all the simulated cases are considered.

When looking at 55 m^2 and 70 m^2 and considering average values, household energy bills surpass 0.1 (10% of the income) for all FR. Besides, FPPRI does not offer significant reductions of FP cases when compared to FPI. In spite of this, FPPRI entails significate savings in EC, both for 55 m^2 dwellings (between 49.22% and 88.45%, with a mean of 49.22%) and 70 m^2 (between 51.25% and 87.88% along with an average of 73.62%). Hence, it can be determined that even considering lower EC thanks to the application of adaptive comfort in FPPRI, D_1 households would have to assign more than 10% of their income to pay the energy bills in all cases and 21.95% for 40 m^2 dwellings.

Table 4
Representative values of the first four socioeconomic deciles. Current values and future prospects of average incomes depending on the inflation rate. Current scenario and 2050.

DECILE	Current Decile representative values (CLP)		2050 representative values for each decile (CLP)					
			IRI1 (3.42%)		IRI2 (6.20%)		IRI3 (8.02%)	
	FROM	TO	FROM	TO	FROM	TO	FROM	TO
D_1	0	48.750	0	152.946	0	376.892	0	671.623
D_2	48.751	74.669	152.947	235.202	376.893	579.590	671.624	1.032.831
D_3	74.97	100.709	235.203	315.956	579.591	778.585	1.032.832	1.387.441
D_4	100.71	125.558	315.957	393.915	778.586	970.692	1.387.442	1.729.775

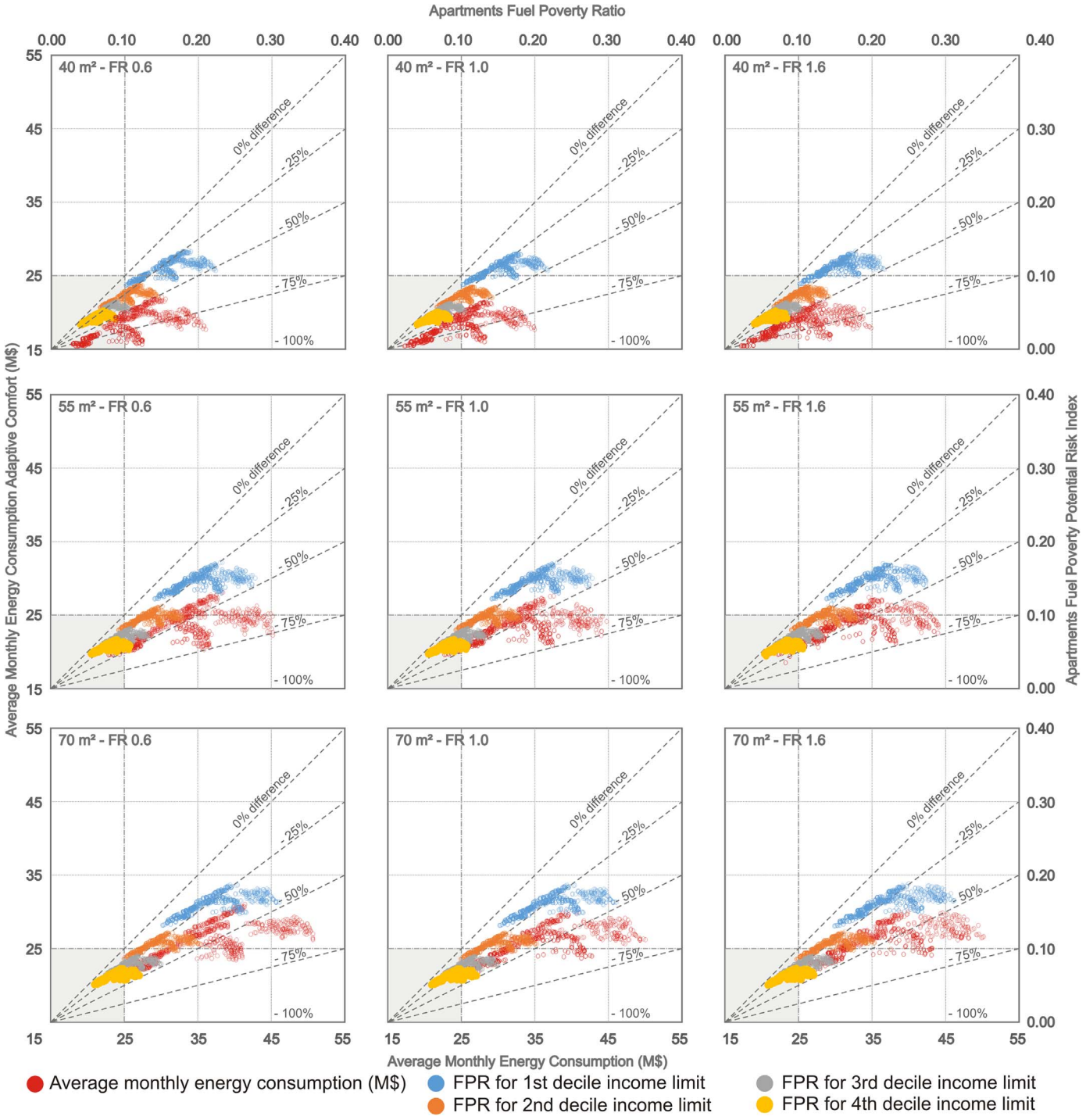
Apartments Fuel Poverty Ratio
40 m² - FR 0.6
40 m² - FR 1.0
40 m² - FR 1.6
55 m² - FR 0.6
55 m² - FR 1.0
55 m² - FR 1.6
70 m² - FR 0.6
70 m² - FR 1.0
70 m² - FR 1.6
0% difference
25%
50%
75%
100%
Average Monthly Energy Consumption Adaptive Comfort (M$)
Apartments Fuel Poverty Potential Risk Index
Average Monthly Energy Consumption (M$)
Average monthly energy consumption (M$)
FPR for 1st decile income limit
FPR for 2nd decile income limit
FPR for 3rd decile income limit
FPR for 4th decile income limit

Fig. 4. Scatter plot. Current relation between average monthly energy consumption (AMEC) and average monthly energy consumption using adaptive comfort (AMECAC) – Fuel Poverty Ratio (FPR) and Fuel Poverty Potential Risk Index Comfort Ratio (FPPRI).

Extrapolating the same analysis for the different deciles, it can be seen that considering the FPPRI, D_2, D_3 and D_4 are not fuel poor when inhabiting 40 m^2 homes. These results differ from the application of FPI, which systematically entails HVAC systems as proposed by the CCS. In this case, the application of FPPRI instead of FPI implies a reduction in FP rates of between 2.93% for D_3 and 52.47% for D_2, demonstrating the relevance of adaptive comfort. This situation is even more patent in 55 m^2 and 70 m^2 homes; in this case, between 26.58% and 65.86% of D_2 households would fall into fuel poverty, with a reduction of between 68.40% and 33.64% respectively. Therefore, D_2 households could be allocated freely in any 40 m^2 dwelling, but only in designated 55 m^2 and 70 m^2 units if FPPRI is used. D_3 and D_4 households could choose any apartment if their EC is kept under 10% of their income using adaptive comfort. The reduction of the FP risk in the D_3 is 2.93% for 40 m^2 homes, 45.56% for 55 m^2 and 59.99 for 70 m^2 homes. For D_4, it would be 7.18% in 55 m^2 homes and 18.79% in 70 m^2, 40 m^2 homes could be freely inhabited disregarding FP as a risk.

3.2. Scenario 01: Inflation Rate for income 1 and inflation rate for energy prices 1

Considering an inflation rate for incomes of 3.42% (IRI1) and 0.97%

for energy prices (IRE1) in 2050, Fig. S1 shows a tendency of a better affordability for energy prices. For 40 m^2 apartments, all the cases are under the 10% limit considering both FPPRI and FPI. Therefore, under these scenarios for 2050, all deciles would be able to afford the energy bill in 40 m^2 homes.

When looking at 55 m^2 and 70 m^2, just the D_1 surpass 0.1 (10% of the income) for all FR considering both FPPRI and FPI indexes. Considering the FPPRI, D_2, D_3 and D_4 are not fuel poor when inhabiting 40 m^2, 55 m^2 and 70 m^2 homes. However, if FPI is considered, fuel poverty appears in 1.08% of households inhabiting apartments of 55 m^2, regardless of the FR of the considered dwelling, likewise 29.28% will be fuel poor for 70 m^2.

3.3. Scenario 02: inflation rate for income 2 and inflation rate for energy prices 3

Considering an inflation rate for incomes of 6.20% (IRI2) and 6.22% for energy prices (IRE3) a new scenario can be devised for year 2050 (Fig. S2), characterized by less affordable energy bills. In 40 m^2 apartments, most of the D_1 cases (88.81%) fall into FP considering FPI whereas, if the analysis is carried out with FPPRI, only a few are over the 10% limit (14.43%). In 55 m^2 homes, just the D_1 surpass 0.1 for all FR considering FPPRI. If the analysis considers the FPI approach, most of D_2 (59.72%) and one tenth of D_3 households pay more than 10% of their incomes, with D_4 being under 10%. In 70 m^2 apartments, D_3 and D_4 households (considering the FPPRI) are always below 10% for all FR. However, half of D_2 households are in FP (49.58%) if the criteria used is FPPRI, whereas when considering FPI, all of them are fuel poor. D_3 and D_4 households surpass the 10% limit in 44.02% and 9.65% of the cases considered, respectively (FPI).

3.4. Scenario 03: inflation rate for income 3 and Inflation Rate for energy prices 1

In this case (Fig. S3), the gap between inflation rates for incomes and energy prices forecasts a scenario of full affordability for all deciles. This scenario applies both for FPI and FPPRI for all deciles, who would be able to inhabit any dwelling with no further problems.

3.5. Scenario 04: inflation rate for income 1 and inflation rate for energy prices 3

A scenario that forecasts higher inflation rates for energy prices than for incomes intensifies the risk of FP (Fig. S4). In this case, 55 m^2 and 70 m^2 dwellings surpass the 10% threshold for all deciles considering both indexes. In the case of 40 m^2, D_1 and D_2 are above 10%; whereas D_3 and D_4 are 85.22% and 1.47% as an average for all FR, respectively.

3.6. Scenario 05: inflation rate for income 3 and inflation rate for energy prices 2

This case, Fig. S5, shows a similar scenario to Fig. S3, as none of the cases are in potential risk considering both FPPRI and FPI.

4. Influence of FPI and FPPRI on the early stages of design

Many scenarios have been brought into discussion, but only some of them have been selected in order to further clarify the influence of FPI and FPPRI on the variety of parameters that should be taken into consideration in the early stages of design:

- FPPRI IRI1-IRE3 (3.42%; 6.22%). In this scenario, income grows steadily but energy prices rise faster, with this being the most disadvantageous way.
- FPPRI IRI2-IRE3 (6.20%; 6.22%). In this context, the growth of energy prices is coupled with that of incomes, being an intermediate scenario.

Both scenarios are compared using the FPPRI index, on the basis of variables that define the flats: Form ratio, location, orientation and urban context; all of them remain crucial in the early stages of design. The aforementioned index evaluates the probability of using more than 10% of the income to pay the energy bill for any given household, in relation to each one of the variables. In such fashion, it is intended to evaluate the flexibility and sensitivity of those selected scenarios.

4.1. Form ratio

For 40 m^2 apartments (Fig. 5) with three possible geometrical configurations at the present time, only the poorest decile D_1 presents a plausible risk of FP, though this is lower in flats featuring an FR of 0.6 (70.02%). This tendency is worsened in 2050 (FPPRI IRI1-IRE3), placing 100% of D_1 and D_2 households at risk of FP disregarding FR; around 85% of D_3 and a negligible amount of D_4 fall into FP (1.47%). In the case of IRI2-IRI3, only the first decile shows a considerable risk, with this being very low for the rest of the households.

When talking about 55 m^2 apartments (Fig. 5), D_1 households are always in FP and D_2 is sensitive to changes in the FR between 1.0 (22.80%) and 0.6 (30.90%). The most disadvantageous future prospects (IRI1-IRE3) extend a risk of 100% through all deciles in contrast with the IRI2-IRE3 scenario, where a drastic effect is observed, D_1 has a FPPRI of 100% and the rest of deciles present a null risk.

At the present time, 70 m^2 dwellings only represent a risk for deciles 1 and 2, being 100% and 65.86% on average, respectively. Just as in the former scenario, IRI1-IRE3 brings a risk of 100% for all households, whereas IRI2-IRI3 only affects D_1 (100%) and D_2, with this risk being on average 40% for all considered FR. It is feasible to shelter the rest of

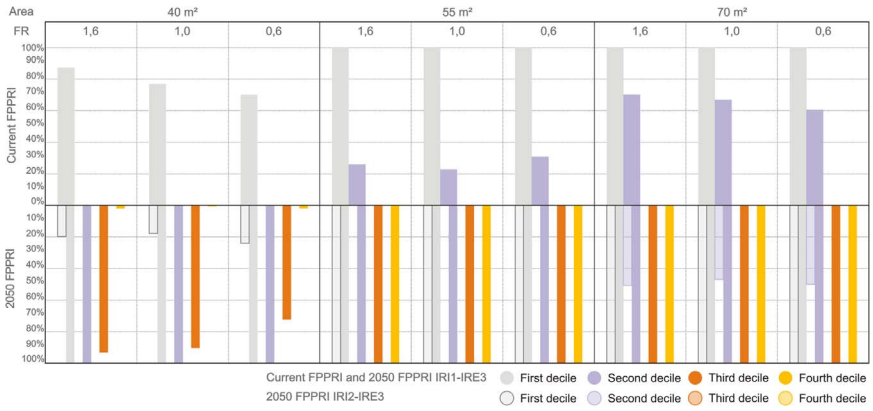

Fig. 5. Comparison of current FPPRI, 2050 FPPRI IRI1-IRE3 and 2050 FPPRI IRI2-IRE3 in terms of form ratio.

households (D_3 and D_4) in any flats, disregarding their FR.

4.2. Location

Regarding the location of flats within the building, units located from the 1st to 3rd floor and whether corner or central positions have been considered. Besides, the area of the flat and form factor have been taken into account. Current situation (Fig. 6) shows that D_1 households have no risk only when inhabiting 40 m^2 units, with an FR of 0.6 or 1.0. When talking about 55 m^2 or 70 m^2 units, the risk is 100%. The next decile, D_2, only faces risk when occupying 55 and 70 m^2 units. The wealthiest deciles, D_3 and D_4, have no risk disregarding location and size of the flat.

Assessing the effect of climate change, taking into account 2050 FPPRI IRI1-IRE3 and IRI2-IRE3 (worst and intermediate scenario), the following considerations can be made. Even in the smallest flats, some locations have a considerable FPPRI, including D_4 households.

However, when considering the most favorable scenario, 40 m^2 central flats offer no risk; only those ones located on the 1st and 3rd floor present some risk, though only for the D_1 households. As for 55 m^2 and 70 m^2 flats, the risk is 100% for all deciles in all locations when considering the 2050 FPPRI IRI1-IRE3 scenario. Therefore, in this worst scenario only the 40 m^2 flats would be affordable.

Considering the 2050 FPPRI IRI2-IRE3 scenario, 55 m^2 and 70 m^2 flats would represent a FPPRI of 100% for D_1, irrespective of their position within the building. FPPRI would fall to zero from 50 m^2 flats for the D_2 decile and so on.

When talking about 70 m^2 flats, the D_2 decile offers some flexibility,

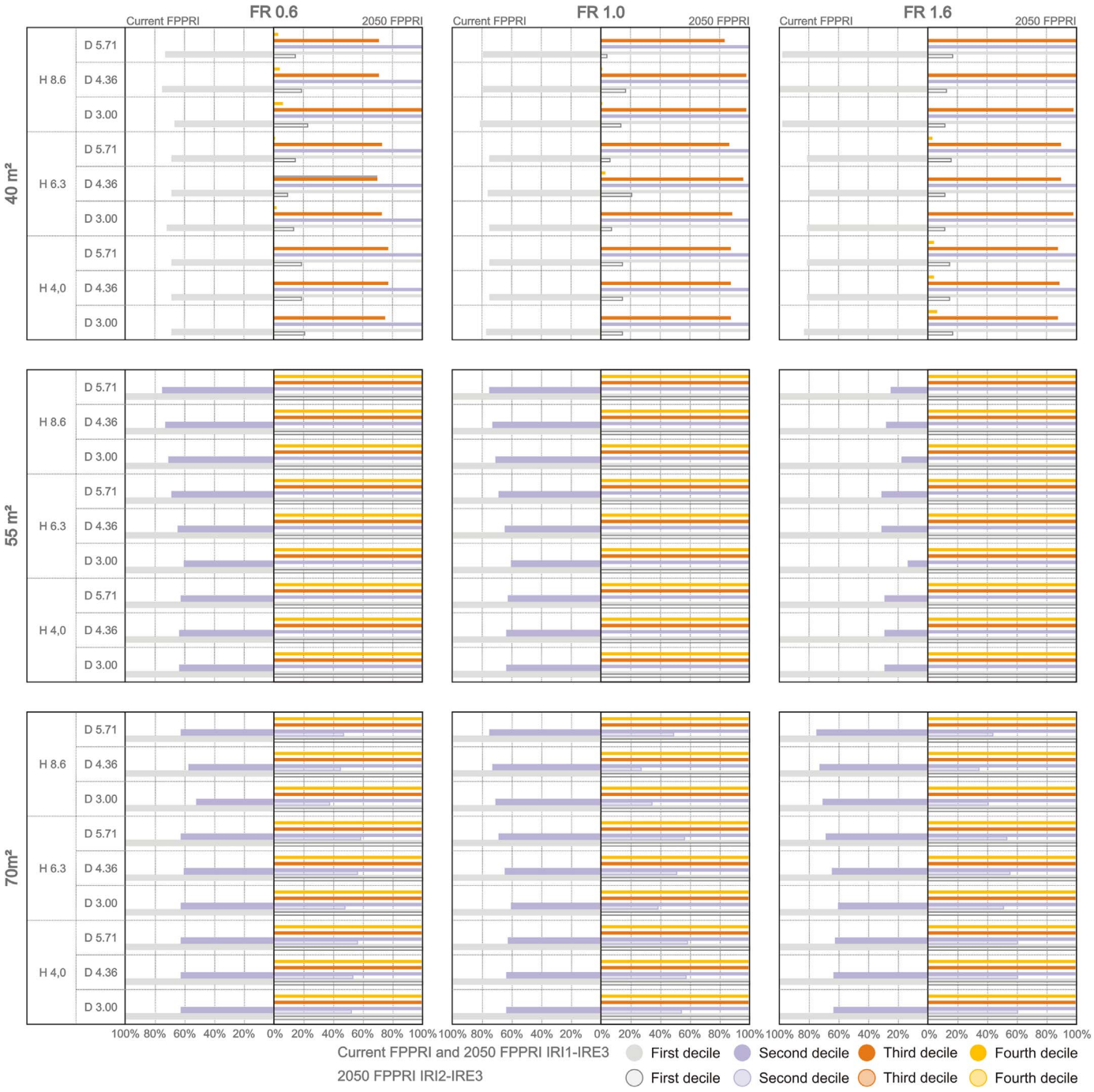

Fig. 6. Comparison of current FPPRI, 2050 FPPRI IRI1-IRE3 and 2050 FPPRI IRI2-IRE3 in terms of spatial location within the building.

depending on the FR and the position of the unit; central units have less risk of FPPRI, being even 0% in 2F-central irrespective of their FR. The rest of deciles (D_3 and D_4) have no risk.

4.3. Orientation

The orientation of each one of the dwellings also has an impact on the potential risk, with some orientations being more beneficial in terms of reducing the risk percentage.

Regarding the current situation (Fig. S6), FPPRI only affects D_1 when inhabiting 40 m^2 flats, as well as D_1 and D_2 in 55 m^2 and 70 m^2. The most beneficial orientation in terms of reducing this risk is North. Comparing these figures with future predictions, 2050 FPPRI IRI1-IRE3 offers worse results. This scenario foresees a considerable risk of FPPRI (80%), even for D_3 deciles and the smallest units, with the impact being reduced when FR equals 0.6. D_3 and D_4 offer a negligible risk. The rest of units (55 m^2 and 70 m^2) offer a potential risk for all deciles in this worst scenario.

With the 2050 FPPRI IRI2-IRE3, the smallest flats have nearly no risk of FPPRI associated with their orientation, being at most 30% for D_1 decile. 55 m^2 flats have a risk of 100% for D_1 households, falling into 0% for the next decile and subsequent ones. As for the biggest units, FPPRI is always 100% for D_1, variable for D_2 and null for the rest (D_3 and D_4).

4.4. Urban context

The influence exerted by nearby structures is also considered (Fig. S7). Separation between blocks has been fixed at D3.00, D4.36 and D5.71 m, which corresponds to the distance where, during winter solstice, direct sunlight impinges on the considered façade, also considering that the adjoining buildings have a height of H4.00, H6.30 and H8.60.

The effect of the different scenarios has a similar pattern to the former ones. Currently, FPPRI only affects the poorest deciles when inhabiting 40 m^2 flats, as well as D_1 and D_2 when inhabiting 55 m^2 and 70 m^2 flats. In the event of the most disadvantageous scenario in 2050, 40 m^2 flats would have a risk over 80% up to D_3 households, where the bigger the FR the higher the risk. In D_3 and D_4 households, the risk is negligible. 55 m^2 and 70 m^2 units, however, pose a considerable and variable risk for all deciles.

In the alternative scenario 2050 FPPRI IRI2-IRE3, the risk derived from nearby structures is minimum for 40 m^2 flats, with the maximum being 30% for D_1 households. For 55 m^2 flats, the risk is 100% for all D_1 households, falling to 0% for D_2 and subsequent ones. The biggest units have a risk of 100% for D_1 families, variable for D_2 and null for D_3 and D_4.

5. Conclusions and policy implications

The main objective of this research is the development of the so-called Fuel Poverty Potential Risk Index (FPPRI) in a context of the changing climate, considering also the forecasted evolution of incomes and energy rates. 186,624 cases comprising the most common typologies of social housing and the 4 most vulnerable deciles amongst low-income households have been assessed. The outcomes show that adequate tools can provide policies with a strong technical basis, allowing for a better implementation. Results have been discussed in two groups: Macro-scale policies, and micro-scale policies.

Macro-scale policies refer to those that tackle with fuel poverty in a general approach. As aforementioned, Chile is implementing a methodology to define fuel poverty (Ministerio de Energía, 2017) with the assistance of the UN. The FPPRI contributes in assessing three factors that, traditionally, have been overlooked in this debate: The role of adaptive comfort of occupants that, in turn, gives a better estimation of the real extent of fuel poverty because it better reflects the behavior of low income residents; the influence of climate change in this phenomenon; the importance of devising a predictive index, transiting in this way from remedial policies to preventive policies.

The national energy plan (Soledad Palma Sierrra and Salvagno, 2016) could be also be benefited from this index. 100% of vulnerable homes are expected to have accessible energy in 2035, so the FPPRI predictions may shed light in clarifying whether this objective may be reached or not. Taking into considerations the conclusions of this research, the FPPRI shows that FP is very sensitive to the relation between energy prices and incomes; so that, taking into consideration that energy in Chile is expensive, the objective of placing Chile into the 5 cheapest countries in terms of energy prices for residential users remains crucial in order to content fuel poverty. According to the results of this research, several combinations between inflation rates for wages and energy prices will produce a scenario where this objective may not be easy to attain.

Also, FPPRI has showed to be much more flexible than traditional FP, because it evaluates a risk, in terms of percentage, rather than the occurrence of a risk itself, in simple terms of yes/no. This allows for more flexible policies that would grade potential fuel-poor residents in terms of their risk, rather than classifying them in closed categories, allowing also for mobility of the dwellers between risk categories depending on the aforementioned relation between decile incomes and energy expenditure. The authors consider that this conclusions help policy-makers in changing their approach towards fuel poverty as a complex, elastic phenomenon with several grades of occurrence.

Micro-scale policies refer to those ones specifically related to the factors involved in the occurrence of fuel poverty. In our case, this factor is the reallocation of vulnerable households into subsidized apartments, who, in turn, compel them to incur into new patterns of energy expenditure. The FPPRI index has been tested considering the architectonic features of social housing complexes (form ratio, location, orientation, urban context and, additionally, apartment area), which has been discussed in Section 4. As a consequence, it is evident that architectonic design has a strong influence on the probability of fuel poverty, and as a consequence policies oriented towards reducing fuel poverty in the lower strata of society that are prone to access a subsidized dwelling should aim at regulating the design of social housing complexes, particularly in their early stages of design, fostering in this way adaptive comfort as a way to reduce the dependence on HVAC systems. Additionally, results suggest that predicted energy expenditure should be regarded as a criteria with legal enforcement when assigning social dwellings to vulnerable households, so that they can be provided not only with decent housing, but also with an affordable housing for their present and future incomes during the expected lifespan of the apartment buildings; 2050 (roughly 30 years lifespan), as undertaken in this research, seems a reasonable period for calculation to be included in a new policy.

Last, but not least, the FPPRI demonstrates the decisive role of adaptive comfort in reducing the risk of fuel poverty, and that heavily relies on the interplay between users and buildings. Educational policies for new residents should also be enacted, though now with legal enforcement but with diffusion campaigns, so that they would know how to regulate themselves the thermal environment of their homes without the use of artificial means when dealing with moderately harsh climates. This also remains crucial because the FPPRI index shows a considerable potential to be used in mild climates, such as the central regions of Chile, or the Mediterranean arch in Europe. It has been concluded, in consequence, that neglecting this interaction may lead to an overestimation of the actual extent of the phenomenon of fuel poverty and a magnification in future enacted policies.

Despite the FPPRI index being high for the lowest deciles, using adaptive comfort would allow them to access a subsidized flat. However, they would have to be carefully allocated with regards to the studied parameters. In this way, the implications of using a mathematical model guarantee equity and social justice, notwithstanding the

detail of specific and casuistic situations not considered in this research, that are always concerned with the ethical and social consequences of using this model. In this way, this research shows that the policies oriented towards fuel poverty could move from a remedial to a predictive approach. However, the model hereby considered is still on an initial stage of development and should be improved in the future by contrasting it with actual data of fuel-poor households, mainly in the Bio-Bio region; crosscheck between predicted data and field measurements will provide with correction factors, with application to the proposed mathematical expression. This will improve its accuracy and provide it with a solid foundation that would lead, in the future, to application to the Chilean legal framework that is being currently being built around the relatively new reality of fuel poverty in this country.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.10.054.

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